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Fiber Element Based Elastic-Plastic Analysis Procedure and Engineering Application

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Abstract

Elastic-plastic time history analysis of super high-rise building is accomplished by the program PERFORM-3D to evaluate the global response and component deformation of structure based on fiber element theory. Direct modeling of a tall building in PERFORM-3D is complicated; hence a pre-process program ETP is established for a more effective and accurate modeling. Analysis improves that fiber element-based nonlinear analysis of the overall structure reveals the macro properties of the structure as well as the force-deformation relationship for the component and stress-strain relationship for the fiber in the micro scope. Finally, the global response, component deformation and energy dissipation of the complicated tall building designed by the current codes subjected to severe ground motions are studied in one engineering practices.

Keywords: elastic-plastic time history analysis, PERFORM-3D, fiber element, super high-rise building, performance-based.

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1. Introduction

The idea of performance based seismic design is a new development direction, which makes a transition of seismic design method from macro qualitative target to micro quantitative target. Elastic-plastic time history analysis is a most reliable method at present and applied to engineering practices increasingly, such as reference(Wang Dasui,2008) using the program ABAQUS and reference(Zhao Fuli,2005) using the program LS-DYNA. This method has been developed grudually, but the following deficiencies still exist: macro deformation of component and energy dissipation time history curve can not be gained directly. In order to solve above problems, a seismic analysis program PERFORM-3D based on fiber element is developed based on DRAIN-3DX in reference(Graham H,2007). Elastic-plastic time history analysis and performance evaluation of a complex super high-rise building is conducted using PERFORM-3D in this paper.

2. Element Models In Perform-3D

2.1 Beam-column element model

PERFORM-3D provides many kinds of beam-column element model, including plastic hinge model and fiber model. The latter is adopted in this paper. The characteristics of fiber model are presented as follow: 1) force-deformation relationship of beams and columns is converted as the stress-strain relationship of concrete and reinforcement; 2) shear deformation is taken into consideration in Timoshenko beam element; 3) a freely selecting input mode of the fiber division is available, by which confined and non-confined concrete fiber and complex composite section can be inputted. And typical sections of the beam-column fiber are shown in Figure 1.

In PERFORM-3D, a function of section assembly for beam-column component, which can increase the number of integral points along element length without increasing the number of degrees, is also provided, and the calculation accuracy and effect can be improved. Beam-column element is usually divided into end plastic region model and multi-segment plastic region mode based on different component assembly, as shown in Figure 2. If element is divided reasonably, it can save computing time when end plastic region model is adopted under the premise of accuracy. Besides, while beam component bearing large shear, shear hinge can be added to simulate nonlinear shear deformation and shear failure of beam with assembling sections.

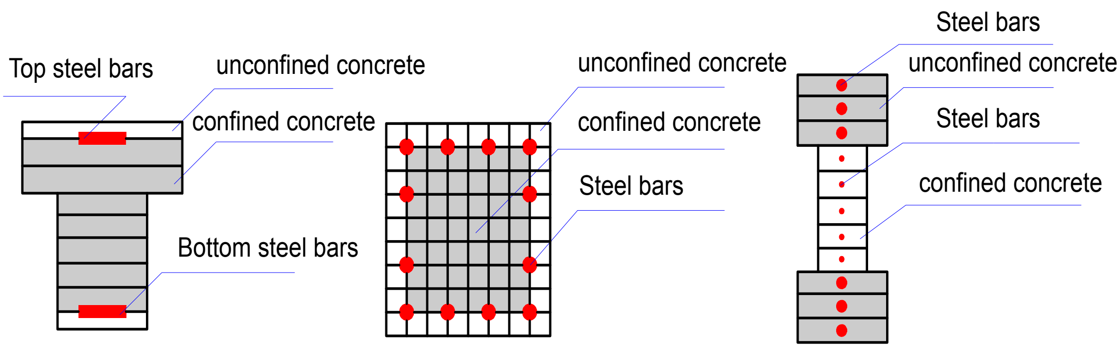


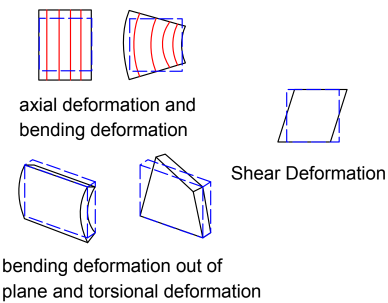
Figure 1: Fiber of beam and column and shear wall

（a）End plastic region model （b）Multi-segment plastic region model

Figure 2: Assembly of beam-column component

2.2 Layered shear wall model

Macro layered element is adopted in PERFORM-3D to simulate shear wall component (Kutay Orakcal,2006), as shown in Figure 3. One dimensional fiber element is used for simulating the compression-bending effect, while using nonlinear or linear shear model for the shear effect in plane and elastic model for the bending and shear and torsional effect out of plane. The characteristics of shear wall are as follows: confined and nonconfined concrete fiber is adopted to simulate end confined region and other nonconfined region respectively when defining fiber sections. The rigid connection between shear wall and beam is rigid arm, as shown in Figure 4.



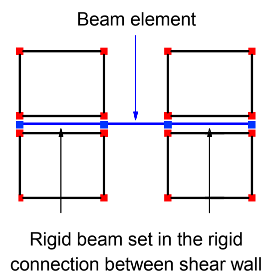


Figure 3: Layered element of shear wall Figure 4: Rigid arm set in shear wall

3. Material Model

3.1 Steel model

Steel model with bulking or non-bulking are available in PERFORM-3D. Because the ductility design is mainly based on the fact that the stress of reinforcement is still in high lever after experienced large cyclic plastic strain and the requirement that reinforcement cannot be abrupted brittly, so nonbulking steel model is always applied for reinforcement(Xu Pei-fu,2005). HRB400 is adopted in this paper, and the model curve of that is shown in Figure 5.

3.2 Concrete model

A macro model with Mander stress-strain relationship is most frequently used to describe working condition of confined concrete in uniaxial compression(J.B.Mander,1984), which is related with section shape and the configuration condition of stirrup. In Perform-3D, the model should be transfered in the standard force-deformation (F-D) relationship which can be determinate by 5 parameters. Hence, concrete model curve adopted in the structure in different confined condition by stirrup can be computed according to the Mander model, mean value of concrete’s strength and elastic modulus, as shown in Figure 6.

3.3 Hysteretic model

As known that energy can be dissipated by nonlinear component under cyclic loading, and amount of the dissipated energy can be represented by the area of hysteretic loop. Hence, to a great extent, the structural response can be differed by the area and shape of hysteretic loop. In PERFORM-3D, parameters of energy degradation are determinate by the maximum deformation and can be specified optionally, as shown in Figure 7. PERFORM-3D gives the required energy degradation through adjusting the unloading-load stiffness, and the coefficient of energy degradation is taken as the ratio of the area of degradated and non-degradated hysteretic loop, which can be obtained from experiment and numerical simulation. In this paper, parameters of energy degradation is defined according to the degradation rule of unloading-load stiffness in Mander model, as shown in Figure 8, while that of reinforcement in all strength region is taken as 1.0.

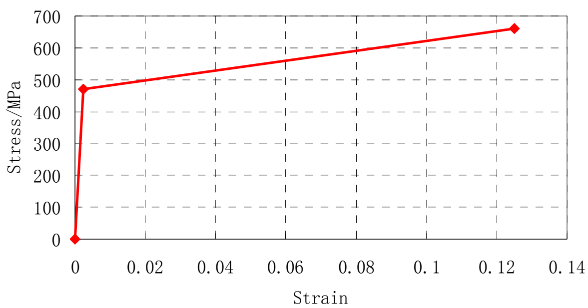


Figure 5: Stress-strain relationship volum-stirrup ratio

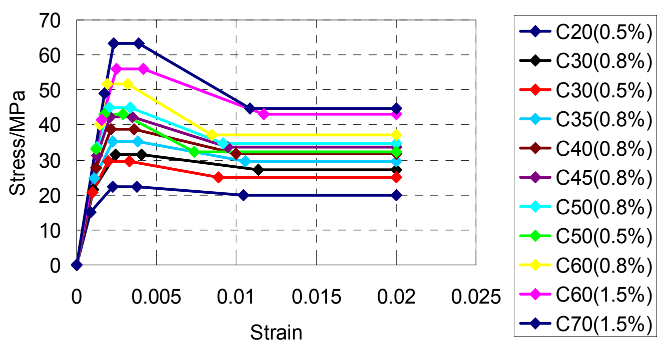


Figure 6: Stress-strain relationship of confined of concrete with different reinforcement

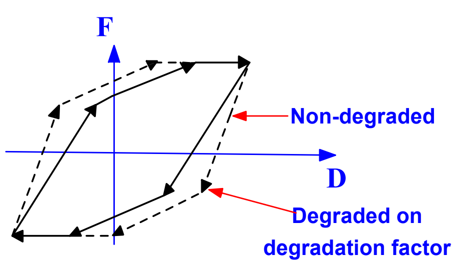


Figure 7: Hysteretic loop of energy degradation

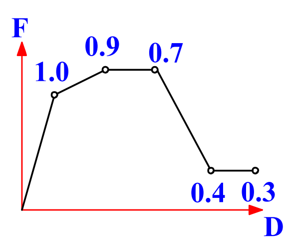


Figure 8: Degradation coefficients of concrete

4. Engineering Project

4.1 Engineering overview

A super high-rise building is composed of two identical 58-storey tall buildings, which has the height of 185.2 m with maximum height-width ratio of 7.1. RC partial frame-supported shear wall is taken as the lateral resistance system of the structure. The frame-shear wall structure is used in the 1st floor, and shear wall structure is used from the 2nd floor to the 58th floor. Partial shear walls are supported by frame-supporting column in the first storey through transfer beam. RC beam is applied for full span transfer beam, while SRC beam is applied for non-full span transfer beam which supporting the shear walls with openings.

Maximal thickness of core tube walls is 600 mm, and decreases to 450mm gradually along the height; the thickness of ambient walls is 800 mm, and remain unchanged along the height; maximal sectional dimension of frame-supporting column is 1400x1200 mm, the dimension of SRC transfer beam is 600x1000 mm, the dimension of RC transfer beam is 900x1000 mm. Concrete strength of vertical component is varied with eight steps, C70 for the bottom and C30 for the 38th storey and above. The arrangement of structural plan is shown in Figure 9.

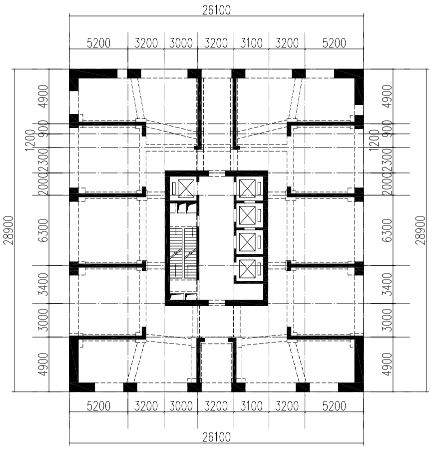


Figure 9: Building plan

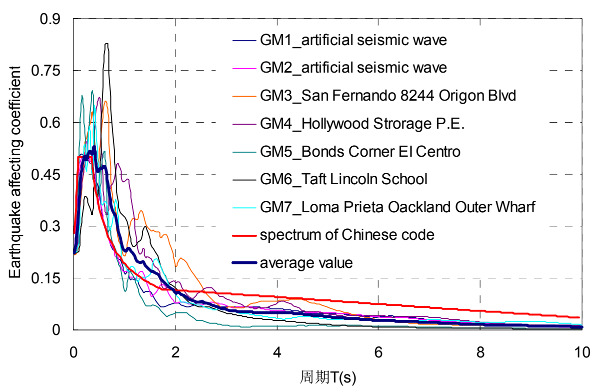


Figure 10: Comparison of response spectrum form the seismic code and seismic waves

4.2 Seismic action

Elastic-plastic time history analysis under rare earthquake (7 degree) is conducted based on PERFORM-3D (HAN Xiao-lei,2008). 2 groups of artificial seismic waves and 5 groups of natural seismic waves are chosen for time history analysis. In trial calculation, 20 groups of two-way natural seismic waves are adopted in elastic model which is modeled in ETABS. Based on comparison of base shear result gained from time history analysis and response spectrum analysis, these seismic waves which meet the needs of the seismic code are chosen. And the screening conditions are as follows: base shear result gained form time history analysis of single wave should be no less than 65% of the result gained form response spectrum analysis and the mean value of the base shear results gained form time history analysis of the chosen waves should be no less than 80% of the result gained form response spectrum analysis. Response spectrum of dominate wave from each chosen group and response spectrum described in the seismic code are shown in Figure 10.

4.3 Structure modeling

Considering the importance of the structure, PERFORM-3D is adopted for static and dynamic elastic-plastic analysis. For PERFORM-3D is a research-type program, it is not convenient for the modeling of complicate high-rise building. In order to solve the pre-processing problem, a visualized modeling pre-processing program of PERFORM-3D named ETP V1.1 is developed. It is convenient to read the information of geometric, section and elastic material, input the section reinforcement of beam, column and shear wall and provide the information of nonlinear material. The complicate high-rise structure can be modeled after these date imported into PERFORM-3D. In order to consider the influence of structural practical reinforcement, the reinforcement of elastic-plastic analysis model is input according to the preliminary design.

4.4 Analysis setting

Structural analysis under vertical load standard combination is conducted prior to elastic-plastic analysis. Vertical load imported from ETABS is applied to the structure. Static elastic-plastic analysis controlled by load shall be adopted in Vertical load analysis for nonlinear model. The analysis results are set as initial state of time history analysis considering P-Δ effect.

Rayleigh damping is used in the analysis with damping ratio of 0.05 in the first two vibration modes. The analysis time is 20s with Step length of 0.02s and substep number of 200. Time history analysis is conducted under 14 load conditions with 7 groups of seismic waves.

5. Analysis Results

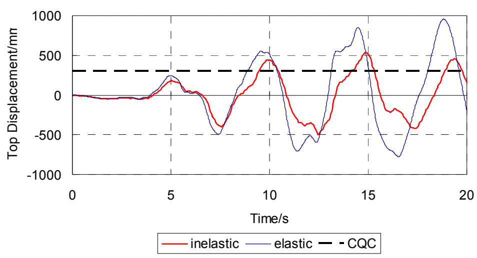
5.1 Structural overall response

In order to have a good inspect of the plastic deformation, structural overall response time history of elastic model (ETABS model) and elastic-plastic model under the same earthquake are compared, taking the condition GM3X for an example, as shown in Fig 11. It can be seen from analysis results that during the first 7s, the results of two models are close to each other which indicates that the structure is still in elastic state. And after 7s, the top displacement results of two models are separated which indicates that the structure has an obvious elastic-plastic damage.

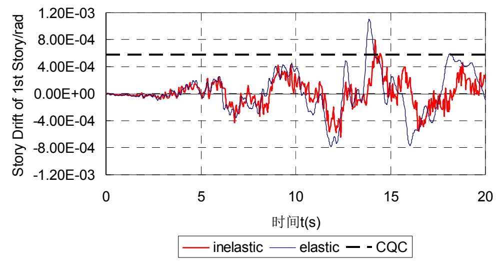
The distance between peak values is increasing with the extension of time, which shows that the structural natural period is become longer because of stiffness degradation due to structural elastic-plastic damage.

It can be known from the comparison of macro deformation and force that, structure has not experienced strong nonlinear state under maximum considered earthquake. Energy dissipation is calculated by PERFORM-3D automatically, as shown in Figure 12, which indicates that structure is in the nonlinear state after 7s, and it also can be seen from the ratio of elastic-plastic energy and modal energy that, structure is still in weakly nonlinear state.

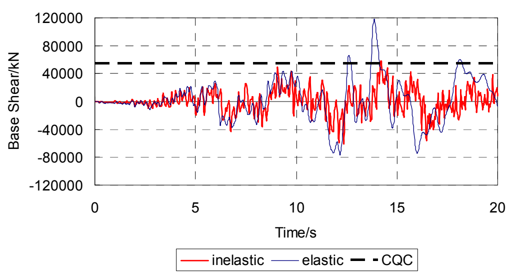
Structural overall responses in X direction under seven seismic waves are shown in Figure 13 and Figure 14. It can be seen that the structure meets the limit value 1/100 of drift specified in the code for elastic-plastic analysis.



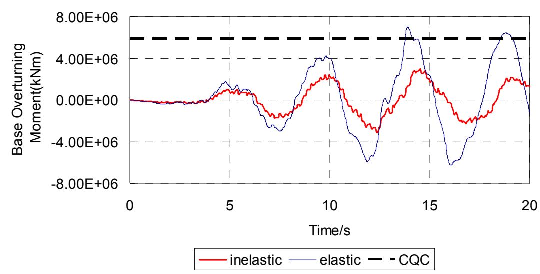
（a）Top displacement



（b）Bottom drift



（c）Base shear



（d）Base bending

Figure 11: Structural responses time history of elastic and elastic-plastic analysis

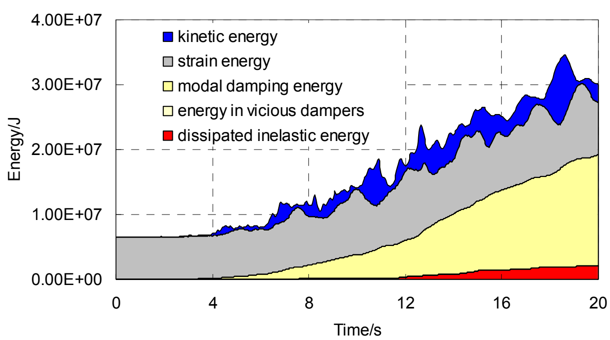


Figure 12: Energy dissipation under condition GM3X

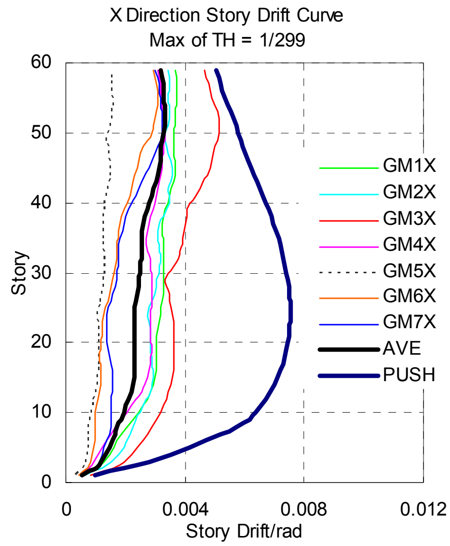


Figure 13: Drift curve under all earthquake condition

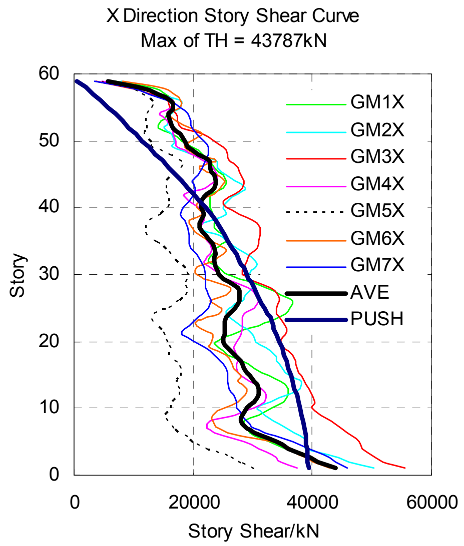


Figure 14: Storey shear curve under all earthquake condition

5.2 Structural component response

According to the regulation about limit value of component's deformation performance index based on Design idea of performance based seismic design (ASCE-41,2007) and taking the practical condition including the construction and force of component as a reference, limit value of performance index is gained , as listed in Table 1.

Table 1: Rotation performance index /rad

Component		IO	LS	CP
Column	Bottom strengthened region	0.003	0.01	0.012
	Non-strengthened region	0.005	0.012	0.016
Beam	Flexural control	0.01	0.02	0.025
	Shear control	0.005	0.01	0.02
Shear wall		0.003	0.006	0.009

Taking condition GM3X for an example, the deformation performance of beam, column and shear wall is shown in Fig 15. It can be seen from Fig 15 that the deformation response of component indicates that structure is in weakly nonlinear state. A small part of beam is in LS and CP state, while most of column and shear walls are in IO state, which shows that components' deformation meets the need of performance index.

The reason for the structure is still in weakly nonlinear state under maximum considered earthquake is that the building is located in Zhuhai where wind pressure is 0.90 kN/m2. Hence, the condition of structural reinforcement is controlled by wind load condition which make sure that the structure is in un-yielding state under design basis earthquake.

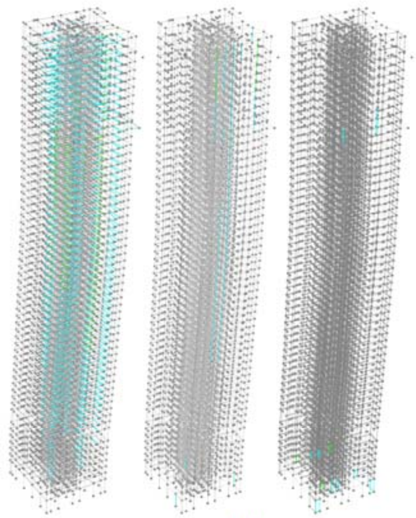


Figure 15: Deformation performance of components under GM3X condition

6. Conclusions

The key of performance based seismic design is the structural elastic-plastic analysis method, and elastic-plastic time history analysis based on fiber model is a most reliable and efficient method at present. Performance based seismic design can be realized through establishing structural elastic-plastic model with PERFORM-3D. A secondary development is applied to pre-processing program of PERFORM-3D, which can make this method applicable to engineering practices.

Analysis improves that fiber element-based nonlinear analysis of the overall structure reveals the macro properties of the structure as well as the force-deformation relationship for the component and stress-strain relationship for the fiber in the micro scope, which can be applied to the structural performance evaluation.

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